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Low-energy precision physics and the high-energy frontier

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Abstract

Despite numerous searches for physics beyond the Standard Model at high-energy colliders and low-energy experiments, no compelling evidence has been found. If this continues to be the case after the LHC has started operating at a centre-of-mass energy of 13 TeV or higher, low-energy precision physics will become even more important in constraining or finding physics beyond the Standard Model. In this article a very basic overview is given over the interplay between high-energy and low-energy observables in uncovering the nature of new physics. To this end an effective theory approach is discussed and examples for its application are given.

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1. Introduction

The Standard Model (SM) is an extremely successful theory. It has passed a very large number of ever more precise experimental tests. Despite all effort, no solid evidence for physics beyond the Standard Model (BSM) at any collider experiment has been found. The recent discovery at CERN of a particle consistent with the long-sought Higgs boson is yet another chapter in this story. Indeed, the couplings of this particle are in very good agreement with what was predicted for the SM Higgs and its mass is also in perfect agreement with what was expected from indirect constraints from precision measurements.

In addition to searches at high-energy colliders, very stringent tests of the SM are being done using low-energy observables. Once more, a large number of measurements show excellent agreement with theoretical predictions within the SM. There are a few cases such as the anomalous magnetic moment of the muon, Bennet et al. in [1], or the proton radius, Antognini et al. in [2], where there is a tension between the prediction and the measurement. However, it is more likely than not that the origin of these small discrepancies is not due to BSM physics.

This leaves us with a peculiar situation in particle physics. On the one hand we have this immensely successful theory. On the other hand we know that the SM cannot provide us with answers to a number of crucial questions. It does neither explain dark matter nor the dominance of matter over antimatter in the universe. It also fails to provide a solution to the so-called strong CP problem and makes no attempt to describe dark energy or gravity to name just some of the shortcomings.

There has been a huge effort in trying to find an extension to the SM that provides answers to at least some of the questions that are unanswered by the SM. This has to be achieved without disturbing the spectacular agreement of theory with collider experiments. The decisive question is at what scale Λ_{UV} does new physics show up. There are good theory arguments to believe that this scale is at around 100 GeV to 1 TeV. However, the lack of any sign of BSM physics at the Large Hadron Collider (LHC) has put these arguments under pressure. Of course, there is another big step ahead with the increase of the centre-of-mass energy at the LHC from 8 TeV to 13 or 14 TeV. If the arguments hinting at $\Lambda_{UV} \sim 1$ TeV are correct, the LHC should be capable of producing at least some of the new particles.

Of course, the high-energy frontier is not the only option to look for BSM physics. Rather than manifesting itself through new particles as external states, BSM can modify processes with only SM external particles through virtual effects. In fact, some of the indirect constraints mentioned above related to the Higgs boson are an interplay of such virtual effects with SM particles in the loop. BSM particles can act in a similar way and modify couplings and cross sections of SM particles. The size of these deviations from the SM depends crucially on the mass scale of the BSM particles and their coupling to SM particles.

Thus, broadly speaking there are two possible scenarios for particle physics in the years ahead. Either the LHC discovers BSM physics and gives us reasonably concrete information about its nature, or the SM continues to pass all tests and constraints on BSM models become even more stringent. As we will discuss in Section 2, in the former case, theory is in very good shape to deal with the challenges ahead. In the latter case, however, it is very likely that we will need to combine information from all possible sources and low-energy observables will play an even more important role. In Section 3 we will describe an effective-theory approach that allows for a general parameterization of BSM physics. Finally, in Section 4 we will consider some typical examples how to use this approach to constrain BSM physics combining data from the high-energy as well as the high-precision frontier.

2. Precision tests at the energy frontier

There has been truly impressive progress in theoretical predictions for high-energy scattering processes. Due to a factorization theorem a scattering process can be split into perturbative and non-perturbative parts. This is illustrated in Fig. 1. The parton distribution functions (PDF) give the probability to find a parton with momentum fraction x_i inside a proton of momentum P_i . This is a universal but non-perturbative quantity that is obtained from global fits. The partons then undergo a hard scattering process and produce a number of hard high-energy partons. During the parton shower multiple predominantly soft and collinear radiation is taken into account. The last two parts can be described perturbatively and it is here where there has been tremendous progress in the past few years. For a recent review see for example Ellis et al. [3].

The state of the art for calculating hard scattering processes is roughly $2 \rightarrow 8$ at LO, $2 \rightarrow 4/5$ at NLO and there is ongoing work for $2 \rightarrow 2$ processes at NNLO. NLO calculations are done in a highly automated fashion. Furthermore, several schemes have been worked out to consistently combine NLO calculations with parton showers. This is non trivial, as care has to be taken not to double count the emission of a soft and/or collinear gluon from a hard parton.

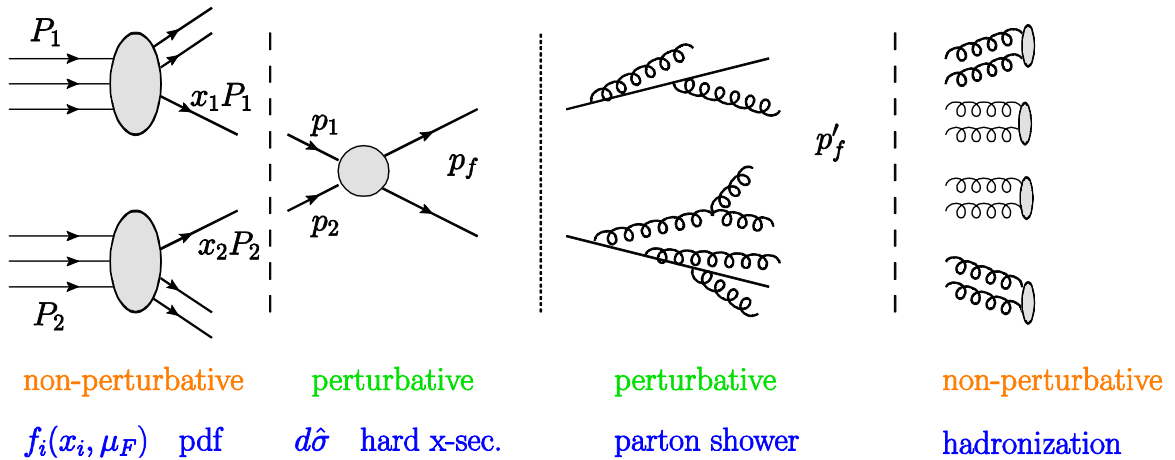


Fig. 1 Schematic picture of a hard scattering process at the LHC.

After the parton shower we are left with a large number of rather soft quarks and gluons which undergo hadronization to form the hadrons observed in the final state. While there has been little progress in the theoretical description of hadronization in the past ten or twenty years, its impact on a typical observable studied at the LHC is rather limited.

Combining the theoretical tools described above with precise experimental data allows for very stringent tests of the SM with experiments at high-energy colliders. Should a BSM particle be produced there are good prospects for it to be studied in detail. But also powerful indirect tests are possible at colliders, such as the search for anomalous couplings and consistency checks between the values of masses and cross sections for SM particles.

3. The SM and beyond as an effective theory

Given the lack of hints from experiment on the nature of BSM it is a somewhat unrewarding task to try to find *the* BSM theory that is realized in nature. A possible way forward is to parameterize our ignorance by treating BSM physics in an effective-theory framework. This builds nicely onto the commonly accepted view that the SM is an effective theory itself, valid up to a certain scale Λ_{UV} . The effects of any BSM physics that is characterized by new fields with a large mass can be described at energies below this scale by higher dimensional operators. These operators are generated by integrating out the heavy BSM fields.

Depending on the (unknown) nature of these fields certain operators are generated, while others will be absent. As a very simple example consider the exchange of a hypothetical heavy particle of mass $M \sim \Lambda_{UV}$ between fermions of the SM ψ_i , as illustrated in Fig. 2. If the exchanged momentum p^2 is much smaller than M^2 , the contribution of this (and similar) diagrams can be approximated by a dimension 6 four-fermion operator (plus a whole tower of even higher-dimensional operators). The nature of the exchanged particle determines the precise form of the four-fermion effective operator. In fact, for any BSM model with additional heavy particles, the coefficients of the various operators can be computed. The advantage of working with the operator rather than a specific model is that the combination of all operators includes all possible models, at least within the approximation taken. Of course, in the limit $p^2 \rightarrow M^2 \sim \Lambda^2$ this approximation is not valid any longer and the effective-theory approach breaks down. Thus, assuming that at some point non-vanishing coefficients for some of these operators are found, it will be a non-trivial task to deduce the BSM model from this knowledge. However, for pinning down possible deviations and combining data from many different experiments within a general approach, the effective-theory approach is a promising way to proceed.

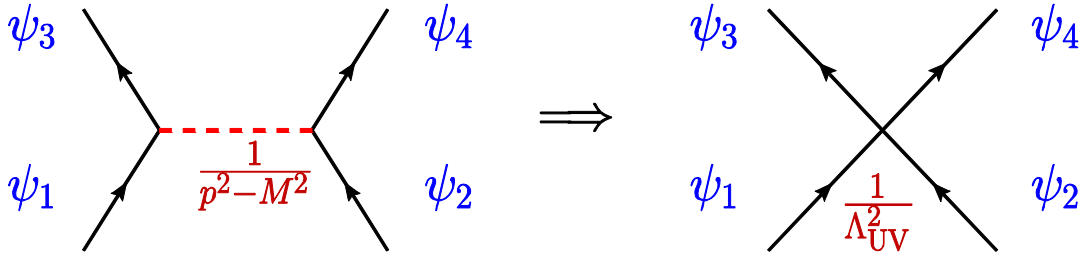


Fig. 2. (a) Diagram in the underlying theory with the exchange of a particle of mass $M \sim \Lambda_{UV}$; (b) Effective dimension 6 operator.

Contrary to the renormalizable operators of the SM that are of dimension $d_{SM} \leq 4$, the BSM operators all are of dimension $d_{BSM} > 4$. Thus they are suppressed by $d_{BSM} - 4$ powers of the large scale Λ_{UV} . Given that there is only one operator of dimension 5, related to neutrino masses, it is reasonable to include in a first step all operators of dimension 6. The only requirement that is made is that the new physics does not break Lorentz invariance and $SU(3) \times SU(2) \times U(1)$ local gauge invariance. Schematically, the Lagrangian then reads

$$L_{BSM} = L_{SM} + \frac{1}{\Lambda_{UV}} \sum_k c_k^{(5)} O_k^{(5)} + \frac{1}{\Lambda_{UV}^2} \sum_k c_k^{(6)} O_k^{(6)} + \dots \quad (1)$$

A complete list of possible operators up to dimension 6 has been given by Buchmüller and Wyler in [4] and later has been refined by Grzadkowski et al. [5]. Assuming baryon number conservation, there are 15 independent operators with no fermion fields, 19 independent operators with two fermion fields and 25 independent four-fermion operators. Of course, operators with fermion fields also have an additional family index. Thus the number of coefficients to be constrained is somewhat daunting. Furthermore, allowing for baryon number violation there are five more operators to be considered. Unfortunately the choice of the set of operators is not unique since the equations of motion can be used to relate various operators and eliminate some in terms of others. We should also mention that not all possible BSM scenarios can be described in this way. For example light but very weakly coupled new fields do not fit in this picture and, by construction, any Lorentz-violating extension of the SM is also not included. However, in the latter case a very similar but generalized approach can be taken, Colladay and Kostelecky [6].

The aim within this framework is to constrain the coefficients C_k of the various operators or, even better, find a non-vanishing coefficient. Strictly speaking, it is always the combination C_k / Λ^2 that enters if an effect of a dimension 6 operator is considered. Thus the importance of such a contribution is affected by the value of the coupling C_k and by the scale Λ_{UV} .

What is the typical scale we would expect the SM to be valid up to? Denoting the Higgs doublet by Φ , the SM Lagrangian contains the term $L_{SM} = C^{(2)} \Lambda^2 \Phi \Phi^\dagger + \dots$ that is responsible for the Higgs mass. From this term we would expect that the mass of the Higgs boson M_H is of the order of Λ_{UV} . Unless we accept some fine tuning with an (as yet unexplained) small coefficient $C^{(2)}$ we would have to conclude that Λ_{UV} is about 100 GeV or 1 TeV at most, given that $M_H \sim 125$ GeV. On the other hand, the complete lack of any hints for BSM physics at the LHC would indicate that Λ_{UV} is much larger than 1 TeV. Such a large value of Λ_{UV} would result in an efficient suppression of all effects of dimension 6 (and higher) operators and would be the most natural explanation for why no deviations from the SM are observed. In particular, if no evidence for BSM is found at the 13/14 TeV LHC, the tension between M_H and Λ_{UV} (related to the hierarchy problem) requires some explanation.

In this context it is very interesting to note that the Higgs mass and the top mass seem to have very particular values. Indeed, the running of the quartic Higgs coupling λ is affected through a top-quark box diagram by the

Higgs-top-Yukawa coupling and hence, the top quark mass. This contribution results in λ decreasing with increasing energy. Of course, we need $\lambda > 0$ in order to have a stable minimum in the Higgs potential. Thus, given M_H and the mass of the top one can ask at what scale does λ turn negative and hence does the SM become inconsistent. A detailed answer to this question depends on several details such as the value of the strong coupling, but essentially the value of the top mass is just right such that the SM can be valid up to very high energies, potentially even up to the Planck scale.

Obviously, none of these arguments are conclusive at all to actually determine Λ_{UV} . However, we might be well advised to prepare for the case where there is no new physics at the TeV scale and the SM is valid to much higher energies. In this case it is well possible that the most stringent tests of the SM and the best chance to find a deviation from the SM come from very precise low-energy experiments. In any case, a unified approach for combining the energy with the precision frontier will be extremely important in this case, as we will discuss in the next section.

4. Combining low-energy constraints with collider searches

As mentioned above, new physics can manifest itself through virtual effects also at energies well below the scale Λ_{UV} . Hence precise low-energy measurements will play a vital role. If new particles are explicitly produced at the LHC, studying the impact of these particles on low-energy observables will give very useful additional information and will be a vital consistency check. On the other hand, if no new particles are produced at the energy frontier and the BSM search focusses on indirect effects, low-energy measurement will be even more important. Indeed, constraining all possible operators (for example of dimension 6) requires the study of a vast amount of processes. However, we should mention that the large number of free couplings introduced by the effective theory is not as limiting as one might think. In fact, for a particular process quite often only a very limited number of these operators (and hence their couplings) contribute. Typically, processes with external massive gauge bosons or fermions of the third family are tested at high-energy colliders. These are basically modern versions of anomalous coupling searches, as described for example in Degrande et al. [7]. On the other hand, very stringent constraints from some low-energy observables, such as electric dipole moments or branching ratios of flavor violating processes like $\mu \rightarrow e \gamma$ or neutron decay correlations often probe some selected operators to much higher values of Λ_{UV} . Thus, the large number of operators in such an effective-theory approach requires a combined approach where as many observables are included as possible.

As an example of the interplay between high-energy and low-energy observables in constraining the effect of possible dimension 6 operators let us mention lepton-flavour violation in the charged sector, as investigated among others by Bhattacharya et al. [8]. Some of the four-fermion operators compatible with gauge invariance give rise to flavour violating processes such as $d \rightarrow u e^- \bar{\nu}$. In particular, there is a scalar operator and a tensor operator with a priori separate and independent coefficients C_S and C_T . These (and other) coefficients then feed into an effective Lagrangian with non-standard charged-current interactions such as

$$L_{cc} \sim G_F [\epsilon_S (\bar{l} \nu) (\bar{u} d) + \epsilon_T (\bar{l} \sigma_{\mu\rho} \nu) (\bar{u} \sigma^{\mu\rho} d)]$$

where ϵ_S and ϵ_T depend on C_S and C_T , $\sigma^{\mu\rho}$ is the usual combination of gamma matrices and G_F is the Fermi constant. Of course, the couplings have to be defined with an ultraviolet subtraction scheme and usually modified minimal subtraction is used.

The partonic process $d \rightarrow u e^- \bar{\nu}$ can manifest itself in different physical processes. At the LHC, a process that is sensitive to this anomalous contribution is $p p \rightarrow e^-$ plus missing energy while the decay $n \rightarrow p e^- \bar{\nu}$ is a low energy process that can give strong constraints. As discussed in Bhattacharya et al. (2011), for the couplings of the scalar and tensor four-fermion operators the LHC and low-energy constraints are of similar power. Using modified minimal subtraction at 2 GeV the limits from 7 TeV LHC with several tens of inverse femtobarn luminosity and current low-energy limits both very roughly result in $|\epsilon_S| < 0.01$ and $|\epsilon_T| < 0.002$. These limits can be substantially improved with a high luminosity LHC run at 14 TeV or with future low-energy measurements.

What is particularly nice in this example is the complementarity of the high- and low-energy approach. Both constraints depend on non-perturbative inputs. In the case of the LHC these are the PDF and for the low-energy observables, the form factors are required. Since it is not always easy to minimize the uncertainty introduced by this non-perturbative contributions it is reassuring to have two different approaches with completely different systematics from the non-perturbative domain.

Of course, this is just one particular example for such an effective-theory analysis and in the literature there are many more, ranging from collider-dominated studies of anomalous triple gauge couplings, Higgs couplings and top couplings to low-energy dominated studies of lepton flavour violating interactions. What is missing at the moment is a more unified approach where a possible connection between the various separate studies is made. However, the vast technical improvement we have witnessed recently in automatizing the calculation of scattering amplitudes and decay processes has not been without impact in this field. Indeed, first steps towards implementing some of the effective operators in computer tools have been made. The goal is to develop tools for automatized evaluation of theoretical predictions for a wide range of observables. This alone is not sufficient since a combination of limits obtained at vastly different energies also requires setting up a consistent scheme to evolve the various couplings to a common scale. Given the renewed interest in this field and the fact that several groups are active, it is not unreasonable to expect that this field develops further into a common framework to hunt for physics beyond the Standard Model.

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